

Search for CP -violating charge asymmetry in $B^\pm \rightarrow J/\psi K^\pm$ decays

K. Sakai,³⁴ T. Kawasaki,³⁴ H. Aihara,⁴⁸ K. Arinstein,^{1,36} T. Aushev,^{22,15} A. M. Bakich,⁴² V. Balagura,¹⁵
E. Barberio,²⁶ K. Belous,¹⁴ V. Bhardwaj,³⁸ B. Bhuyan,¹¹ M. Bischofberger,²⁸ A. Bondar,^{1,36} A. Bozek,³²
M. Bračko,^{24,16} T. E. Browder,⁹ M.-C. Chang,⁵ Y. Chao,³¹ A. Chen,²⁹ K.-F. Chen,³¹ P. Chen,³¹ B. G. Cheon,⁸
C.-C. Chiang,³¹ K. Cho,¹⁹ Y. Choi,⁴¹ J. Dalseno,^{25,44} Z. Doležal,² Z. Drásal,² W. Dungel,¹³ S. Eidelman,^{1,36}
M. Feindt,¹⁸ B. Golob,^{23,16} H. Ha,²⁰ J. Haba,¹⁰ K. Hayasaka,²⁷ H. Hayashii,²⁸ Y. Horii,⁴⁷ Y. Hoshi,⁴⁶ W.-S. Hou,³¹
H. J. Hyun,²¹ K. Inami,²⁷ R. Itoh,¹⁰ M. Iwabuchi,⁵³ Y. Iwasaki,¹⁰ J. H. Kang,⁵³ H. Kawai,³ H. Kichimi,¹⁰
C. Kiesling,²⁵ H. J. Kim,²¹ J. H. Kim,¹⁹ Y. J. Kim,⁷ B. R. Ko,²⁰ S. Korpar,^{24,16} P. Krizán,^{23,16} P. Krokovny,¹⁰
T. Kuhr,¹⁸ T. Kumita,⁴⁹ A. Kuzmin,^{1,36} Y.-J. Kwon,⁵³ S.-H. Kyeong,⁵³ J. S. Lange,⁶ M. J. Lee,⁴⁰ J. Li,⁹
A. Limosani,²⁶ C. Liu,³⁹ D. Liventsev,¹⁵ R. Louvot,²² A. Matyja,³² S. McOnie,⁴² K. Miyabayashi,²⁸ H. Miyata,³⁴
Y. Miyazaki,²⁷ G. B. Mohanty,⁴³ D. Mohapatra,⁵¹ E. Nakano,³⁷ M. Nakao,¹⁰ Z. Natkaniec,³² S. Neubauer,¹⁸
S. Nishida,¹⁰ O. Nitoh,⁵⁰ S. Ogawa,⁴⁵ T. Ohshima,²⁷ S. Okuno,¹⁷ S. L. Olsen,^{40,9} G. Pakhlova,¹⁵ H. Palka,³²
C. W. Park,⁴¹ H. Park,²¹ H. K. Park,²¹ R. Pestotnik,¹⁶ M. Petrič,¹⁶ L. E. Piilonen,⁵¹ M. Prim,¹⁸ M. Röhrken,¹⁸
S. Ryu,⁴⁰ H. Sahoo,⁹ Y. Sakai,¹⁰ O. Schneider,²² A. J. Schwartz,⁴ K. Senyo,²⁷ O. Seon,²⁷ M. E. Sevier,²⁶
M. Shapkin,¹⁴ C. P. Shen,⁹ J.-G. Shiu,³¹ B. Shwartz,^{1,36} F. Simon,^{25,44} P. Smerkol,¹⁶ A. Sokolov,¹⁴
E. Solovieva,¹⁵ S. Stanič,³⁵ M. Starič,¹⁶ K. Sumisawa,¹⁰ T. Sumiyoshi,⁴⁹ G. N. Taylor,²⁶ Y. Teramoto,³⁷
K. Trabelsi,¹⁰ T. Tsuboyama,¹⁰ S. Uehara,¹⁰ T. Uglov,¹⁵ Y. Unno,⁸ S. Uno,¹⁰ G. Varner,⁹ K. E. Varvell,⁴²
K. Vervink,²² C. H. Wang,³⁰ M.-Z. Wang,³¹ P. Wang,¹² M. Watanabe,³⁴ Y. Watanabe,¹⁷ R. Wedd,²⁶ E. Won,²⁰
Y. Yamashita,³³ C. C. Zhang,¹² Z. P. Zhang,³⁹ P. Zhou,⁵² T. Zivko,¹⁶ A. Zupanc,¹⁸ and O. Zyukova,^{1,36}

(The Belle Collaboration)

¹*Budker Institute of Nuclear Physics, Novosibirsk*

²*Faculty of Mathematics and Physics, Charles University, Prague*

³*Chiba University, Chiba*

⁴*University of Cincinnati, Cincinnati, Ohio 45221*

⁵*Department of Physics, Fu Jen Catholic University, Taipei*

⁶*Justus-Liebig-Universität Gießen, Gießen*

⁷*The Graduate University for Advanced Studies, Hayama*

⁸*Hanyang University, Seoul*

⁹*University of Hawaii, Honolulu, Hawaii 96822*

¹⁰*High Energy Accelerator Research Organization (KEK), Tsukuba*

¹¹*Indian Institute of Technology Guwahati, Guwahati*

¹²*Institute of High Energy Physics, Chinese Academy of Sciences, Beijing*

¹³*Institute of High Energy Physics, Vienna*

¹⁴*Institute of High Energy Physics, Protvino*

¹⁵*Institute for Theoretical and Experimental Physics, Moscow*

¹⁶*J. Stefan Institute, Ljubljana*

¹⁷*Kanagawa University, Yokohama*

¹⁸*Institut für Experimentelle Kernphysik, Karlsruher Institut für Technologie, Karlsruhe*

¹⁹*Korea Institute of Science and Technology Information, Daejeon*

²⁰*Korea University, Seoul*

²¹*Kyungpook National University, Taegu*

²²*École Polytechnique Fédérale de Lausanne (EPFL), Lausanne*

²³*Faculty of Mathematics and Physics, University of Ljubljana, Ljubljana*

²⁴*University of Maribor, Maribor*

²⁵*Max-Planck-Institut für Physik, München*

²⁶*University of Melbourne, School of Physics, Victoria 3010*

²⁷*Nagoya University, Nagoya*

²⁸*Nara Women's University, Nara*

²⁹*National Central University, Chung-li*

³⁰*National United University, Miao Li*

³¹*Department of Physics, National Taiwan University, Taipei*

³²*H. Niewodniczanski Institute of Nuclear Physics, Krakow*

³³*Nippon Dental University, Niigata*

- ³⁴Niigata University, Niigata
³⁵University of Nova Gorica, Nova Gorica
³⁶Novosibirsk State University, Novosibirsk
³⁷Osaka City University, Osaka
³⁸Panjab University, Chandigarh
³⁹University of Science and Technology of China, Hefei
⁴⁰Seoul National University, Seoul
⁴¹Sungkyunkwan University, Suwon
⁴²School of Physics, University of Sydney, NSW 2006
⁴³Tata Institute of Fundamental Research, Mumbai
⁴⁴Excellence Cluster Universe, Technische Universität München, Garching
⁴⁵Toho University, Funabashi
⁴⁶Tohoku Gakuin University, Tagajo
⁴⁷Tohoku University, Sendai
⁴⁸Department of Physics, University of Tokyo, Tokyo
⁴⁹Tokyo Metropolitan University, Tokyo
⁵⁰Tokyo University of Agriculture and Technology, Tokyo
⁵¹IPNAS, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061
⁵²Wayne State University, Detroit, Michigan 48202
⁵³Yonsei University, Seoul

We present the result of a search for charge asymmetry in $B^\pm \rightarrow J/\psi K^\pm$ decays using 772×10^6 $B\bar{B}$ pairs collected at the $\Upsilon(4S)$ resonance by the Belle detector at the KEKB asymmetric-energy e^+e^- collider. The CP -violating charge asymmetry is measured to be $A_{CP}(B^+ \rightarrow J/\psi K^+) = [-0.76 \pm 0.50 \text{ (stat)} \pm 0.22 \text{ (syst)}]\%$.

PACS numbers: 11.30.Er, 13.25.Hw

Violation of CP symmetry in the Standard Model (SM) has been well established. Interest has now shifted to the search for new sources of CP violation due to physics beyond the SM, since the CP violation content of the SM does not explain the matter-antimatter asymmetry of the Universe [1]. In the SM, CP -violating phenomena in the quark sector are described by the Kobayashi-Maskawa theory [2], in which a single irreducible complex phase gives rise to all CP -violating asymmetries. The decay $B^+ \rightarrow J/\psi K^+$ is mediated by a color-suppressed $\bar{b} \rightarrow \bar{c}c\bar{s}$ transition, where the dominant $\bar{b} \rightarrow \bar{c}$ tree-level amplitude and the $\bar{b} \rightarrow \bar{s}$ penguin amplitude have a small relative complex phase, $\arg[-V_{cs}V_{cb}^*/V_{ts}V_{tb}^*]$ [2] in the SM [3]. The charge asymmetry in the decay $B^+ \rightarrow J/\psi K^+$ is defined as

$$A_{CP}(B^+ \rightarrow J/\psi K^+) = \frac{\mathcal{B}(B^- \rightarrow J/\psi K^-) - \mathcal{B}(B^+ \rightarrow J/\psi K^+)}{\mathcal{B}(B^- \rightarrow J/\psi K^-) + \mathcal{B}(B^+ \rightarrow J/\psi K^+)},$$

where \mathcal{B} denotes the branching fraction. Direct CP violation would appear as a nonzero $A_{CP}(B^+ \rightarrow J/\psi K^+)$ value and is predicted to be quite small, $\simeq 0.3\%$ [4], in the SM. Some new physics models predict enhanced values of this asymmetry [4]. For example, a model with an extra $U(1)'$ gauge boson [5] and another model with an extra coupling to the charged Higgs boson [6] predict asymmetries of $\mathcal{O}(1\%)$ and $\mathcal{O}(10\%)$, respectively.

The $B^+ \rightarrow J/\psi K^+$ decay mode has low backgrounds and a large branching fraction, when compared to that of other charmonium decay modes. These properties enable a precise $A_{CP}(B^+ \rightarrow J/\psi K^+)$ measurement, which

provides an important test of various new physics models and constrains their parameter spaces.

The current world average for $A_{CP}(B^+ \rightarrow J/\psi K^+)$ is $(0.9 \pm 0.8)\%$ [7] which is dominated by the D0 result, $(0.75 \pm 0.61 \pm 0.30)\%$ [8], while the most precise result from an e^+e^- collider experiment is the BABAR result of $(3.0 \pm 1.4 \pm 1.9)\%$ [9].

In this paper, we report a measurement of $A_{CP}(B^+ \rightarrow J/\psi K^+)$ using a 711 fb^{-1} data set that contains 772×10^6 $B\bar{B}$ pairs. The $B^+ \rightarrow J/\psi K^+$ decay is reconstructed in the $J/\psi \rightarrow \ell^+\ell^-$ ($\ell = e$ or μ) channels. For a precise measurement of the charge asymmetry in this decay, the asymmetry of charged kaon detection efficiencies must be carefully studied and corrected for. The asymmetry in detection efficiency arises due to the asymmetric geometry of the detector, different interaction rates of kaons in the detector material, and differences in kaon identification efficiencies for K^+ and K^- .

KEKB is an asymmetric electron-positron storage ring that collides 8.0 GeV electrons with 3.5 GeV positrons at the $\Upsilon(4S)$ resonance (center-of-mass [c.m.] energy $\sqrt{s} = 2E_{\text{beam}} = 10.58 \text{ GeV}$). The $\Upsilon(4S)$ resonance is boosted by $\beta\gamma = 0.425$ [10]. The Belle detector is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter (ECL) comprised CsI (Tl) crystals located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located out-

side of the coil is instrumented to detect K_L^0 mesons and to identify muons (KLM). The detector is described in detail elsewhere [11, 12].

Hadronic events are initially selected by requiring at least three reconstructed charged tracks, a total reconstructed ECL energy in the c.m. in the range $0.1\sqrt{s} - 0.8\sqrt{s}$, at least one large-angle cluster in the ECL, a total visible energy – calculated from all charged tracks and isolated neutral showers – greater than $0.2\sqrt{s}$, an absolute value of the z component of the c.m. momentum less than $0.5\sqrt{s}$, and a reconstructed primary vertex that is consistent with the known location of the interaction point. To suppress two-jet non- $\Upsilon(4S)$ background relative to $B\bar{B}$ events, we require $R_2 < 0.5$, where R_2 is the ratio of the second to zeroth Fox-Wolfman moments [13]. To remove charged particle tracks that are poorly measured or do not come from the interaction region, we require $dz < 5$ cm for all tracks, where dz is the absolute value of the coordinate along the beam direction at the point on the track closest to the origin.

The J/ψ meson is reconstructed from one tightly and one loosely identified lepton. For muon tracks, the tight identification criterion is based on track penetration depth and hit scatter in the KLM system, while the loose identification criterion requires only that the tracks have an energy deposit in the ECL that is consistent with that of a minimum ionizing particle. Electron tracks are tightly identified by a requirement on a combination of dE/dx from the CDC, E/p (E is the energy deposit in the ECL and the p is momentum measured by the SVD and the CDC), and shower shape in the ECL. For loose identification, either dE/dx or E/p is required to be consistent with the electron hypothesis. We correct for final-state radiation or bremsstrahlung in the inner parts of the detector by including in the e^+e^- invariant mass calculation the four-momentum of every photon detected within 0.05 rad of the original electron or positron direction. Since small residual radiative tails still remain, we use asymmetric invariant mass requirements, $-60 \text{ MeV}/c^2 < M_{\mu^+\mu^-} - m_{J/\psi} < 36 \text{ MeV}/c^2$ and $-150 \text{ MeV}/c^2 < M_{e^+e^-(\gamma)} - m_{J/\psi} < 36 \text{ MeV}/c^2$, for the $\mu^+\mu^-$ and e^+e^- pairs, respectively.

The combined information from the CDC, TOF, and ACC is used to form a $K - \pi$ likelihood ratio, $\mathcal{R}_K = \mathcal{L}_K/(\mathcal{L}_K + \mathcal{L}_\pi)$, where $\mathcal{L}_{K(\pi)}$ is the likelihood of the kaon (pion) hypothesis. We require $\mathcal{R}_K > 0.6$ for kaon candidates, which is approximately 80% efficient for kaons, while giving a misidentification probability of below 10% for pions.

Charged B mesons are reconstructed by combining a J/ψ candidate with a charged kaon candidate. The energy difference, $\Delta E \equiv E_{\text{cand}} - E_{\text{beam}}$, and the beam-energy constrained mass, $M_{\text{bc}} \equiv \sqrt{E_{\text{beam}}^2 - \mathbf{p}_{\text{cand}}^2}$, are used to separate signal from background [E_{cand} and \mathbf{p}_{cand} are the B candidate energy and momentum, calculated in the $\Upsilon(4S)$ c.m. system, after performing a mass- and

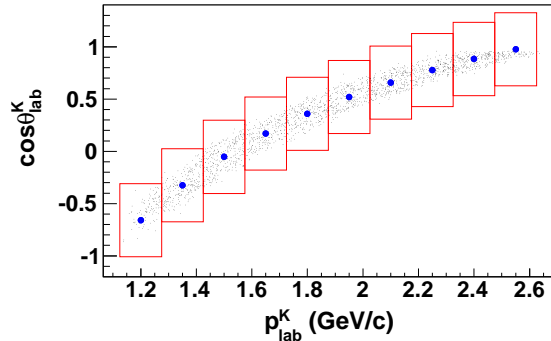


FIG. 1: (color online). Illustration of the $(p_{\text{lab}}^K, \cos \theta_{\text{lab}}^K)$ binning. p_{lab}^K is divided into ten bins each with a width of 0.15 GeV/c. The $\cos \theta_{\text{lab}}^K$ bin width is 0.7, and fully contains the $B^+ \rightarrow J/\psi K^+$ signal. The bins are centered at the kinematically determined values for the two-body decay (blue circles). The small black dots in the figure are $B^+ \rightarrow J/\psi K^+$ events generated by a Monte Carlo simulation.

vertex-constrained fit to the leptons from the J/ψ decay].

In order to determine the signal yield and charge asymmetry, we fit M_{bc} distributions after requiring $|\Delta E| < 40$ MeV. Each M_{bc} distribution for $5.2 \text{ GeV}/c^2 < M_{\text{bc}} < 5.3 \text{ GeV}/c^2$ is fitted with the sum of a Gaussian for the signal and an ARGUS function [14] for background. We simultaneously fit the B^+ and B^- distributions with common shape parameters for the signal and background, except for the mean of the signal Gaussians. In the fit we assume that there is no asymmetry in the background; the effect of a possible asymmetry is included in the systematic error evaluation. We neglect a small contribution from correlated B background, which peaks at the signal position in the M_{bc} distribution. The effect of this “peaking background” is included in the systematic error as described below. Shape parameters and normalizations are allowed to vary in the fit. To correct for the kaon detection asymmetry, which depends on the momentum p_{lab}^K and polar angle $\cos \theta_{\text{lab}}^K$ of kaons in the laboratory system, we perform fits in ten bins of $(p_{\text{lab}}^K, \cos \theta_{\text{lab}}^K)$. The binning is shown in Fig. 1. The bins are labeled 1 to 10 with increasing p_{lab}^K . We observe a total signal yield of $41,315 \pm 205$ events. The M_{bc} distribution for all bins combined is shown in Fig. 2. The measured raw asymmetry ($A_{\text{CP}}^{\text{raw}}$) in each bin is given in Table I.

We measure the kaon detection asymmetry, $A_{\epsilon}^{K^+}$, in data using $D_s^+ \rightarrow \phi \pi^+$ ($\phi \rightarrow K^+ K^-$) and $D^0 \rightarrow K^- \pi^+$ decay modes [15]. Here, we denote $A^{x^+} \equiv \frac{N^{x^+} - N^{x^-}}{N^{x^+} + N^{x^-}}$. The measured asymmetries of the above modes can be written as

$$\begin{aligned} A_{\text{rec}}^{D_s^+} &= A_{\text{FB}}^{D_s^+} + A_{\epsilon}^{\pi^+} \\ A_{\text{rec}}^{D^0} &= A_{\text{FB}}^{D^0} + A_{\epsilon}^{\pi^+} - A_{\epsilon}^{K^+}, \end{aligned}$$

assuming the asymmetries are small. Here A_{FB} denotes

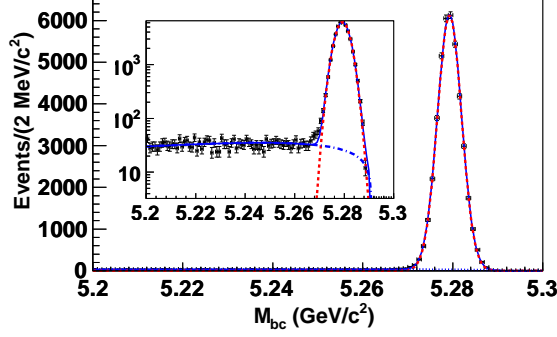


FIG. 2: (color online). M_{bc} distribution of $B^+ \rightarrow J/\psi K^+$ candidates summed over all bins and for both B charge states (inset plot is on a semilog scale). The blue solid, blue dot-dashed, and red dashed curves are the total fit, the background and the signal components, respectively.

the forward-backward asymmetry due to the $\gamma^* - Z^0$ interference in $e^+e^- \rightarrow c\bar{c}$ and $A_{\epsilon}^{\pi^+}$ is the pion detection asymmetry. We can extract $-A_{\epsilon}^{K^+}$ by subtracting the $A_{\text{rec}}^{D_s^+}$ value from the $A_{\text{rec}}^{D^0}$ with the assumption $A_{\text{FB}}^{D_s^+} = A_{\text{FB}}^{D^0}$. This assumption is reasonable because the effect of the fragmentation on the forward-backward asymmetry is expected to be small. Possible deviations from this assumption are checked in data and included as a small contribution to the systematic error. The subtraction is performed in bins of pion momentum, p_{lab}^{π} , and polar angle in the laboratory system, $\cos\theta_{\text{lab}}^{\pi}$, and the charmed meson's polar angle in the c.m. system, $\cos\theta_{\text{CMS}}^D$ (since $\cos\theta_{\text{CMS}}^D$ is correlated with $\cos\theta_{\text{lab}}^{\pi}$ and $A_{\text{FB}}^{D_s^+}$ depends on it).

We reconstruct $D_s^+ \rightarrow \phi\pi^+$ and $D^0 \rightarrow K^-\pi^+$ decays with charged tracks that originate from the vicinity of the interaction point. We require $\mathcal{R}_K > 0.6$ for kaons and $\mathcal{R}_K < 0.4$ for pions. The ϕ meson candidates are selected with the requirement $1.00 \text{ GeV}/c^2 < M_{K^+K^-} < 1.04 \text{ GeV}/c^2$. To remove D_s^+ and D^0 mesons produced in B meson decays, we require the charmed meson momentum in the c.m. system be greater than $2.5 \text{ GeV}/c$. The invariant mass distributions of $D_s^+ \rightarrow \phi\pi^+$ and $D^0 \rightarrow K^-\pi^+$ candidates after these requirements are shown in Figs. 3.

We first obtain the $A_{\text{rec}}^{D_s^+}$ map in three-dimensional (3D) bins of $(p_{\text{lab}}^{\pi}, \cos\theta_{\text{lab}}^{\pi}, \cos\theta_{\text{CMS}}^D)$. In each bin, $A_{\text{rec}}^{D_s^+}$ is obtained by fitting the reconstructed D_s^+ candidate mass distributions ($1.89 \text{ GeV}/c^2 < M_{\phi\pi^+} < 2.09 \text{ GeV}/c^2$). The fits are performed in a manner similar to those performed for $B^+ \rightarrow J/\psi K^+$. D_s^+ signals are parameterized as a sum of two Gaussian functions and a bifurcated Gaussian, which represents the tail of the distribution (for high-statistics bins only). The bin-dependent fractions of Gaussians are fixed to those obtained from Monte Carlo simulations. The background is parametrized as a

first-order polynomial and its asymmetry is allowed to vary in the fits. Figure 4 shows the $A_{\text{rec}}^{D_s^+}$ map in bins of $(p_{\text{lab}}^{\pi}, \cos\theta_{\text{lab}}^{\pi}, \cos\theta_{\text{CMS}}^D)$. The 3D binning ($3 \times 3 \times 3$) is selected to have sufficient granularity with large enough statistics in each bin.

The $A_{\epsilon}^{K^+}$ values are extracted using $D^0 \rightarrow K^-\pi^+$ decays as follows: fits are performed to the D^0 candidate invariant mass distribution in $1.79 \text{ GeV}/c^2 < M_{K^-\pi^+} < 1.99 \text{ GeV}/c^2$ with a parameterization similar to that used for the D_s^+ . Here $N_{\text{rec}}^{D^0}$ and $N_{\text{rec}}^{\bar{D}^0}$ are corrected according to the $A_{\text{rec}}^{D_s^+}$ values in bins of $(p_{\text{lab}}^{\pi}, \cos\theta_{\text{lab}}^{\pi}, \cos\theta_{\text{CMS}}^D)$. The obtained values of $N_{\text{rec}}^{D^0}$ and $N_{\text{rec}}^{\bar{D}^0}$ are already corrected for A_{FB} and $A_{\epsilon}^{\pi^+}$ and their asymmetry gives $-A_{\epsilon}^{K^+}$. The values of the kaon asymmetry $A_{\epsilon}^{K^+}$ are determined for different $(p_{\text{lab}}^K, \cos\theta_{\text{lab}}^K)$ bins defined in Fig. 1. These results are shown in Fig. 5 and the obtained kaon asymmetry values are quoted in the last column of Table I.

Finally, the measured A_{CP}^{raw} values are corrected by $A_{\epsilon}^{K^+}$ in each bin. The results are shown in Fig. 6 and summarized in Table I. We obtain $A_{CP}(B^+ \rightarrow J/\psi K^+) = (-0.76 \pm 0.50)\%$, which is a weighted average of corrected asymmetries, and in which the error includes only the statistical error of the A_{CP}^{raw} determination. The weights in the averaging procedure are also based only on the statistical error of the A_{CP}^{raw} . Statistical and systematic uncertainties of $A_{\epsilon}^{K^+}$ are included in the systematic error as described below.

TABLE I: Summary of asymmetries (in units of %). A_{CP} is the corrected charge asymmetry. The final A_{CP} values are weighted averages with the statistical errors from A_{CP}^{raw} . The first error in $A_{\epsilon}^{K^+}$ is the statistical error of the $D^0 \rightarrow K^-\pi^+$ signal yield. The second error comes from the statistical errors in $A_{\text{rec}}^{D_s^+}$ and has correlation among bins.

Bin	A_{CP}	A_{CP}^{raw}	$A_{\epsilon}^{K^+}$
1	+0.75	+2.30 ± 2.47	-1.55 ± 0.35 ± 0.26
2	-1.91	-1.04 ± 1.49	-0.86 ± 0.24 ± 0.22
3	-2.23	-1.65 ± 1.47	-0.58 ± 0.23 ± 0.21
4	-0.36	+0.16 ± 1.46	-0.52 ± 0.22 ± 0.19
5	-0.41	+0.01 ± 1.46	-0.42 ± 0.21 ± 0.18
6	-2.52	-2.19 ± 1.42	-0.33 ± 0.20 ± 0.18
7	+1.05	+1.04 ± 1.41	+0.01 ± 0.20 ± 0.19
8	-0.14	+0.20 ± 1.41	-0.35 ± 0.22 ± 0.23
9	-0.23	-0.01 ± 1.57	-0.22 ± 0.24 ± 0.24
10	-0.63	-0.68 ± 2.61	+0.05 ± 0.27 ± 0.24
Total	-0.76	-0.33 ± 0.50	-0.43 ± 0.07 ± 0.17

Systematic errors arise from three sources: the systematic uncertainty in A_{CP}^{raw} measurement, the uncertainty of the $A_{\epsilon}^{K^+}$ due to $A_{\text{rec}}^{D_s^+}$ and due to $A_{\text{rec}}^{D^0}$. The systematic errors are summarized in Table II. The systematic uncertainties due to the choice of binning, fit range, and mass windows are estimated from variations of the fit results, obtained by refitting the data using different choices.

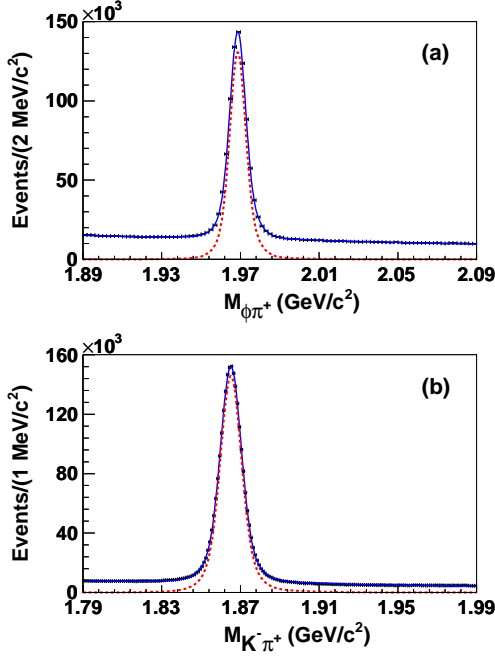


FIG. 3: (color online). $D_s^+ \rightarrow \phi\pi^+$ (a) and $D^0 \rightarrow K^-\pi^+$ (b) invariant mass distribution summed over all bins including the charge-conjugate final states. The blue curve shows the results of the fit described in text, and the red dashed curve shows the signal.

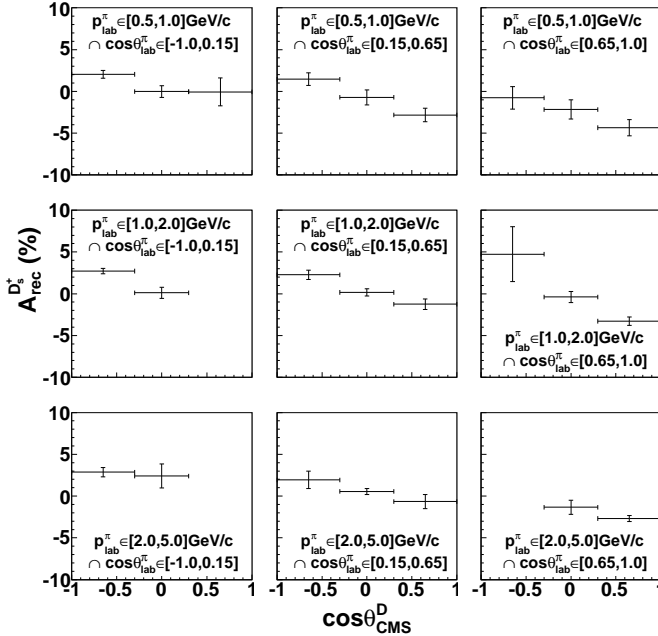


FIG. 4: $A_{\text{rec}}^{D_s^+}$ map in bins of $(p_{\text{lab}}^{\pi}, \cos\theta_{\text{lab}}^{\pi}, \cos\theta_{\text{CMS}}^D)$. The errors shown here are the statistical errors in the $D_s^+ \rightarrow \phi\pi^+$ signal yield. The empty bins do not contain enough D_s^+ candidates to obtain $A_{\text{rec}}^{D_s^+}$ and hence we assign the value of 0.0%.

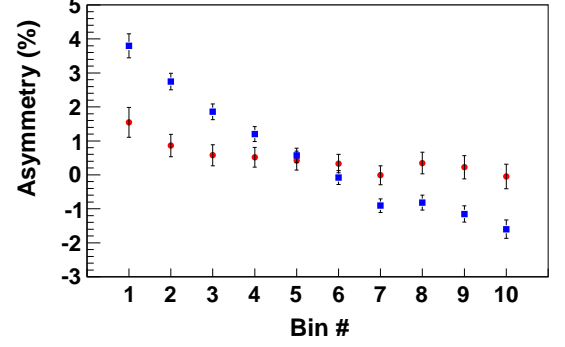


FIG. 5: (color online). $A_{\text{rec}}^{D^0}$ (blue squares) and corrected $A_{\text{rec}}^{D^0}$ (red circles), which corresponds to $-A_{\epsilon}^{K^+}$ in $(p_{\text{lab}}^K, \cos\theta_{\text{lab}}^K)$ bins. The errors in the corrected values of $A_{\text{rec}}^{D^0}$ include the statistical errors of the $A_{\text{rec}}^{D_s^+}$.

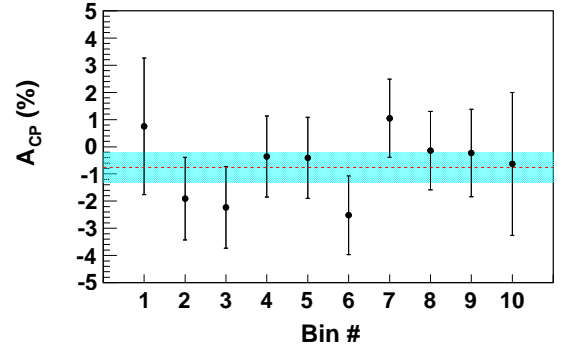


FIG. 6: (color online). A_{CP} distribution in different bins. Errors are obtained from A_{CP}^{raw} and $A_{\epsilon}^{K^+}$ uncertainties summed in quadrature. The red dashed line shows the weighted average of A_{CP} and its uncertainty is shown as the light-blue band. The values obtained in the ten $(p_{\text{lab}}^K, \cos\theta_{\text{lab}}^K)$ regions are consistent with each other.

The dominant systematic error comes from the uncertainty in $A_{\text{rec}}^{D_s^+}$, in which the statistical error in $D_s^+ \rightarrow \phi\pi^+$ signal yields contributes 0.17%. The choice of 3D binning in $(p_{\text{lab}}^{\pi}, \cos\theta_{\text{lab}}^{\pi}, \cos\theta_{\text{CMS}}^D)$ contributes 0.08%. The kaon detection asymmetry in $\phi \rightarrow K^+K^-$ cancels if the momentum distributions of K^+ and K^- are identical in D_s^+ decay. We find a small difference between them that arises from asymmetry in the helicity angle distribution due to the interference between the ϕ and S -wave component in $D_s^+ \rightarrow K^+K^-\pi^+$ decay. We estimate the effect on our measurement to be 0.05% from the difference of momentum distributions in data. The effect of empty bins in the $A_{\text{rec}}^{D_s^+}$ map is estimated by setting $A_{\text{rec}}^{D_s^+}$ values of empty bins to $\pm 2\%$ and results in a negligibly small contribution of 0.001%. The uncertainty in $A_{\text{rec}}^{D^0}$ mainly comes from the statistical errors in the $D^0 \rightarrow K^-\pi^+$ (0.07%) and $(p_{\text{lab}}^K, \cos\theta_{\text{lab}}^K)$ binning

(0.04%). A possible CP asymmetry in the $D^0 \rightarrow K^- \pi^+$ final state arises from the interference between decays with and without $D^0 - \bar{D}^0$ mixing. The uncertainty is estimated from the 95% confidence level upper limit on the CP -violating asymmetry, $A_{CP}^{D^0} = -y \sin \delta \sin \phi \sqrt{R}$ [16], using the world average of $D^0 - \bar{D}^0$ mixing and CP violation parameters [17] and is found to be 0.01%. $A_{CP}^{D_s^+}$ is much smaller than $A_{CP}^{D^0}$ because there is no mixing between D_s^+ and D_s^- . We estimate the effect (0.01%) due to the possible difference between $A_{FB}^{D_s^+}$ and $A_{FB}^{D^0}$; we compare A_{FB} in $D_s^+ \rightarrow \phi \pi^+$ and $D^+ \rightarrow \phi \pi^+$ decays. In addition to binning, the following sources are considered for the uncertainty in A_{CP}^{raw} . Based on the Monte Carlo simulation, we estimate that the peaking background contributes 0.12% of the signal. The dominant contribution comes from $B^+ \rightarrow \bar{D}^0 \pi^+$ with $\bar{D}^0 \rightarrow K^+ \pi^-$ where the $\pi^+ \pi^-$ tracks are misidentified as $\ell^+ \ell^-$, and from $B^+ \rightarrow J/\psi K^*(892)^+$. We estimate the systematic error (0.01%) using $A_{CP}(B^+ \rightarrow \bar{D}^0 \pi^+) = 0.8 \pm 0.8\%$ [18] and $A_{CP}(B^+ \rightarrow J/\psi K^*(892)^+) = -4.8 \pm 3.3\%$ [9]. The systematic error due to possible asymmetry in non-peaking background (0.022%) is estimated by repeating fits allowing the background asymmetry to vary.

The measurement and correction for kaon detection asymmetry is verified by repeating the whole procedure with different requirements on kaon identification. The corrected A_{CP} values are stable within the statistical uncertainty and estimated systematic error.

Adding all systematic errors above in quadrature, the total systematic error is estimated to be 0.22%.

TABLE II: Summary of systematic uncertainties.

	Source	%
A_{CP}^{raw}	Peaking background	0.01
	ARGUS background	0.02
	M_{bc} bin width	< 0.01
	$(p_{\text{lab}}^K, \cos \theta_{\text{lab}}^K)$ binning	0.02
$A_{\text{rec}}^{D_s^+}$	$D_s^+ \rightarrow \phi \pi^+$ statistics	0.17
	$M_{\phi \pi^+}$ bin width	< 0.01
	$M_{\phi \pi^+}$ mass window	0.02
	$(p_{\text{lab}}^+, \cos \theta_{\text{CMS}}^+, \cos \theta_{\text{lab}}^+)$ binning	0.08
	Empty bins	< 0.01
	$\phi \rightarrow K^+ K^-$ asymmetry	0.05
$A_{\text{rec}}^{D^0}$	$D^0 \rightarrow K^- \pi^+$ statistics	0.07
	$M_{K^- \pi^+}$ bin width	< 0.01
	$M_{K^- \pi^+}$ mass window	< 0.01
	$(p_{\text{lab}}^K, \cos \theta_{\text{lab}}^K)$ binning	0.04
	possible $A_{CP}^{D^0}$	0.01
	$A_{FB}^{D_s^+} = A_{FB}^{D^0}$ assumption	0.01
Total		0.22

In conclusion, using 772×10^6 $B\bar{B}$ meson pairs, we have measured the CP -violating charge asymmetry $A_{CP}(B^+ \rightarrow J/\psi K^+)$ to be $(-0.76 \pm 0.50 \pm 0.22)\%$, where the first uncertainty is statistical and second is systematic. No significant evidence of CP violation is observed. Our measurement is consistent with the world average

$(0.9 \pm 0.8)\%$ [7]. This result significantly improves the precision from previous measurements at e^+e^- collider experiments [9, 19] and supersedes our earlier result [20]. The Belle result is slightly more precise than the D0 measurement [8]. The two most precise measurements to date differ by less than two standard deviations.

We thank the KEKB group for excellent operation of the accelerator, the KEK cryogenics group for efficient solenoid operations, and the KEK computer group and the NII for valuable computing and SINET3 network support. We acknowledge support from MEXT, JSPS and Nagoya's TLPRC (Japan); ARC and DIISR (Australia); NSFC (China); MSMT (Czechia); DST (India); MEST, NRF, NSDC of KISTI, and WCU (Korea); MNiSW (Poland); MES and RFAAE (Russia); ARRS (Slovenia); SNSF (Switzerland); NSC and MOE (Taiwan); and DOE (USA).

-
- [1] A.D. Sakharov, Pis'ma Zh. Eksp. Teor. Fiz. **5**, 32 (1967) [JETP Lett. **5**, 24 (1967)].
 - [2] M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49**, 652 (1973).
 - [3] Charge-conjugate states are implied throughout this paper unless stated otherwise.
 - [4] W.-S. Hou, M. Nagashima, and A. Soddu, arXiv:hep-ph/0605080.
 - [5] V. Barger, C.-W. Chiang, P. Langacker, and H.-S. Lee, Phys. Lett. B **598**, 218 (2004).
 - [6] G.-H. Wu and A. Soni, Phys. Rev. D **62**, 056005 (2000).
 - [7] K. Nakamura *et al.* (Particle Data Group), J. Phys. G **37**, 075021 (2010).
 - [8] V.M. Abazov *et al.* (DØ Collaboration), Phys. Rev. Lett. **100**, 211802 (2008).
 - [9] B. Aubert *et al.* (BABAR Collaboration), Phys. Rev. Lett. **94**, 141801 (2005).
 - [10] S. Kurokawa and E. Kikutani, Nucl. Instr. and Meth. A **499**, 1 (2003), and other papers included in this volume.
 - [11] A. Abashian *et al.* (Belle Collaboration), Nucl. Instr. and Meth. A **479**, 117 (2002).
 - [12] Z. Natkaniec *et al.* (Belle SVD2 Group), Nucl. Instr. and Meth. A **560**, 1 (2006).
 - [13] G.C. Fox and S. Wolfram, Phys. Rev. Lett. **41**, 1581 (1978).
 - [14] H. Albrecht *et al.* (ARGUS Collaboration), Phys. Lett. B **241**, 278 (1990).
 - [15] B.R. Ko *et al.* (Belle Collaboration), Phys. Rev. Lett. **104**, 181602 (2010).
 - [16] A.A. Petrov, Phys. Rev. D **69**, 111901(R) (2004).
 - [17] E. Barberio *et al.* (Heavy Flavor Averaging Group), arXiv:0808.1297v3 and online update at <http://www.slac.stanford.edu/xorg/hfag/>.
 - [18] K. Abe *et al.* (Belle Collaboration), Phys. Rev. D **73**, 051106(R) (2006).
 - [19] G. Bonvicini *et al.* (CLEO Collaboration), Phys. Rev. Lett. **84**, 5940 (2000).
 - [20] K. Abe *et al.* (Belle Collaboration), Phys. Rev. D **67**, 032003 (2003).